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Analysis of the self-loosening of packages impact limiter fastening bolts under vibrations during transport

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Abstract

Bolted impact limiters generally equip extremities of packages used to transport irradiated fuel or high-level waste. These shock absorbers, whose mass can reach 2 tons for some package designs, commonly include steel casing filled with wooden blocks aiming at absorbing mechanical impacts and protecting the closure system of the package containment system in case of fire.

Over the last 5 years, around twenty events were declared in France after the observation, during the package unloading operations, that some of these bolts could be loosened by hand.

The causes identified by the package designers and the involved consignors, such as non-compliances in the tightening operations, have led to additional controls of the bolt tightening before shipment. The decrease in the number of events declared subsequently show that these actions seem to be relevant but not sufficient to completely solve this issue.

In this regard, IRSN decided to analyse the phenomenon which can initiate a self-loosening of the fixing bolts of the impact limiters. Several theoretical and experimental studies performed in the past decades show that a self-loosening of fastening bolts can be generated under external loads and vibrations. This phenomenon basically depends on the geometry of the bolt design (diameter, length and thread pitch), the mass of the bolted components and the vibrations transmitted by the transport frame.

It especially appears that the bolts self-loosening is favoured by an unsufficient tightening torque, the use of lubricant on the bolt threads and the vibrations characterised by high frequencies and amplitudes in the perpendicular axis of the bolts.

Considering the vibrations measurements performed during road and rail transports, these conclusions conducted IRSN to recommend, when possible, an increase in the tightening torque of the impact limiters fastening bolts for some package designs.

The first results of this analysis also put in the light the necessity to perform a dedicated experimental program to determine precisely under which conditions the self-loosening of packages impact limiter fastening bolts is initiated.

Introduction

Most of the packages used to transport fissile material, fuel assemblies or waste are equipped with impact limiters whose role is firstly to absorb mechanical energy in case of impact and secondly to ensure a thermal protection of the closure components of the containment system in case of fire. These impact limiters, generally made up of steel casing filled with wooden blocks, are fixed on the extremities of packaging body using fastening bolts which are tightened by torque wrenches.
Since 2011, 20 events have been declared in France after the observation, during unloading operations of packages, that one or several of these bolts could be loosened “by hand”. In particular, 17 of these events have concerned type B packages used to transport spent fuel assemblies between French nuclear power plants and the AREVA reprocessing plant located in La Hague.

Analysis of the events noticed during unloading operations

A dedicated working group, involving the French competent authority (ASN), the French Institute for Radiation Protection and Nuclear Safety (IRSN), the AREVA TN company and the French nuclear operator EDF, was created to discuss possible causes of these events and actions to be put in place in order to reduce their occurrence. In this framework, it has been supposed that the bolts self-loosening could be a consequence of non-compliances of the tightening operations. These deviations could be due to human errors affecting the bolts tightening order and uncompleted operating instructions concerning notably, on the one hand the localisation of the grease on the bolts external surfaces and, on the other hand the waiting period before the application of the torque value specified by the package designer. It has to be noticed that this last point aims to prevent the bolts loosening resulting from differential thermal expansion of the components.

An update of the operating documents and the implementation of additional controls realized before shipment, such as a dual inspection of the bolt tightening using two different torque wrenches and performed by two different operators, have enabled to decrease the occurrence of this type of events. Nevertheless, due to the most recent events, additional operational measures or package design modification, such as an increase of the torque value applied to the impact limiters fixing bolts, are still under discussion in the working group.
In this context, to focus the discussion of the working group on relevant actions, IRSN has performed a review of the available literature related to the bolts self-loosening, especially to identify the origins of such phenomenon. In addition, IRSN has decided to initiate experiments in cooperation with the AREVA TN company to determine precisely the influence of several parameters on the self-loosening of the impact limiter fastening bolts.

Theoretical and experimental studies relative to the bolts self-loosening phenomenon

Bolts self-loosening phenomenon occurs in a large number of applications and has been extensively studied. According to a bibliography including theoretical and experimental studies, a decrease of the bolt pre-load can occur either with or without rotation of the bolt. Bolt loosening without rotation could be a result of differential thermal expansion of the bolted components or plastic deformation, leading to initial stress relaxation. Furthermore, rotation of the bolt is a consequence of an external load or vibrations.

As described hereinafter, several analysis and theories have been conducted and developed in the past decades in order to explain and to quantify the bolts self-loosening phenomenon. The theories developed in the present article are not exhaustive as many variants are available in the literature. Nevertheless, they illustrate the most common physical approaches considered to analyse the phenomenon of bolts self-loosening.

Propagation of impact stress waves [REF 1]

The theory proposed in 1970 by Koga [REF 1] is based on the propagation of impact stress waves in the bolt. In this approach, the compressive waves due to the impact can induce tensile stresses after being reflected at the bolt end.

Self-loosening occurs when the tensile stress reflected in the nut is greater than the compression stress on the lower thread surface. Based on analytical calculations and experiments, the author has shown that the thread angle, the thread pitch and the screw end shape have an impact on the waves reflection and therefore on the risk of self-loosening under external loads. In this regard, the risk of self-loosening is reduced for bolts whose characteristics are presented in table 1.

Table 1: Bolts characteristics to reduce the self-loosening risk [REF 1]

	Bolts characteristics to minimize the self-loosening
Ratio thread pitch / bolt diameter	0.1, 0.125 or 0.15
Thread angle	62°, 62.5° or 63°

The calculations performed by Kuga [REF 1] also conclude that bolts with a thread angle lower or equal to 60° are more subjected to the risk of self-loosening.

Loosening due to transverse vibration [REF 2]

One of the most well-known theories related to the self-loosening of threaded fasteners has been proposed in 1969 by Junker [REF 2]. This theory is based on the principle that bolt self-loosening is the result of relative movements between the threads of the bolt and nut when the external load is greater than the frictional resisting force generated by the bolt’s pre-load. Under repeated transverse movements, this mechanism can lead to a complete bolt loosening.

The main conclusion of this theory is that dynamic transverse loads are more likely to generate a self-loosening than axial loads due to greater radial movements under bolts head. The conclusion of this analysis has been confirmed experimentally using a dedicated device allowing the evaluation of the sensitivity of various fastener designs in terms of self-loosening.
One of the main results of this analysis is that the bolt loosening essentially depends on the amplitude of the transverse displacements but is independent of the vibrations frequency.

Plastic deformation with alternate bending [REF 3]

The impact of cyclic transverse loads on bolt loosening has also been studied by Nassar and Housari [REF 3]. The model developed is based on the principle that a transverse load inducing a plastic deformation of the bolts threads leads to a decrease of the tensile stress in the bolt. In addition, the sliding under the bolt head due to cyclic loads can induce a bending moment in the bolt leading to its loosening. This model has been completed by experimental tests. Results obtained highlight that the risk of self-loosening is:

- decreased for non-greased threads (sliding is reduced),
- increased when the bolted components are subjected to low frequencies vibrations; according to the authors, high frequencies vibrations reduce the sliding duration under the bolt head at each cycle.

Loosening under elastic torsion [REF 4]

According to the model proposed by Yamamoto and Kasei [REF 4], the cause of bolts self-loosening is the elastic torsion generated in the bolt shank due to relative movements in the bolts threads.
The authors developed an equation to determine the transverse force required to lead to a bolt bending and to a self-loosening. This value depends on several parameters, such as the bolt pre-load, the bolt dimensions and the friction coefficient under the bolt head.
In particular, an increase of the pre-load and the friction coefficient lead to higher transverse forces necessary to initiate a self-loosening.

Inclined plan theories [REF 5]

Another common approach consists of an analogy with an inclined plan, where the threads of the bolt are simulated by an inclined plan and the bolt by a mass placed on the plane surface. In this analogy, the mass can slide down the plan – i.e., the bolt can loosen - if the external force, depending on the vibratory motion, exceeds the friction force.

The variant presented by Fernando [REF 5] to evaluate the bolt loosening mechanism is similar to the mechanism of a vibratory conveyor transporting a particle up a ramp (see Figure 1). In this approach, a vibration ($d_0(t) = d_0.\cos(\omega.t)$) drives the particle up the ramp if the upward force generated by the vibration is greater than the resultant of gravitational force (m.g) and static friction

(F) depending on the friction coefficient of the surface (μ).

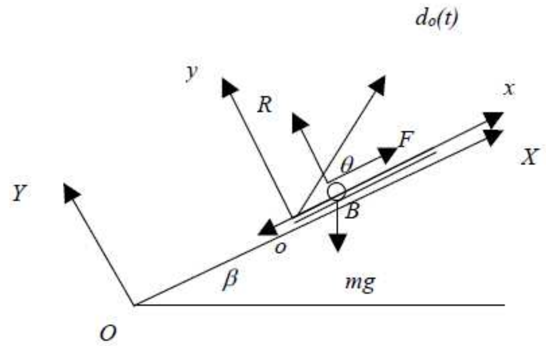

Figure 1: Forces on a particle on a conveyor

Fernando first calculated the movement of the particle according to the vibration properties (direction θ, amplitude d_0 and frequency $\omega/2\pi$) and the plane characteristics (inclination β and friction coefficient μ).

Then, equations have been applied to a bolted assembly considering a pre-loaded bolt and the bolt threads acting as the ramp. In this analogy, the resultant of the bolt pre-load, the frictional force under the bolt head and the gravitational force have been combined. These calculations allow to evaluate the minimum frequency and amplitude of vibrations required to start loosening according to the bolts characteristics and the tightening parameters (pre-load, friction coefficient …). This approach puts in the light that:

- the vibration frequency leading to a bolt self-loosening is higher when the bolt pre-load is increased,
- low friction coefficients in the threads and under the bolts head increase the risk of self-loosening.

Besides, it is demonstrated that bolts with coarse threads and low thread angles are more subjected to the risk of self-loosening, especially when submitted to transverse vibrations.

Main conclusions of the theoretical and experimental studies

All the theoretical approaches and experimental tests procedures available in the literature do not necessarily present similar conclusions regarding the parameters having an influence on the bolts self-loosening. In particular, there is no consensus on the impact of the vibrations frequency on the self-loosening phenomenon. Nevertheless, the most advanced theories tend to prove that the self-loosening is favoured by **vibrations characterised by high frequencies and amplitudes**. Moreover, the following main parameters are generally accepted by the majority of the authors:

- **dynamic transverse loads** are more likely to generate a bolt self-loosening than dynamic axial loads;
- the main reason for a bolt self-loosening is an **insufficient pre-load** in the bolt; a pre-load higher than approximately 65% of the bolt yield strength is generally considered to prevent

any loosening due to vibration levels commonly experienced;

- bolts self-loosening is reduced when the threads are **clean** and **not greased**;
- in order to reduce bolts self-loosening, the use of long bolts with a small diameter and fine-pitch threads is suggested.

Application to the design of the packages impact limiter fastening bolts

The recommendations presented hereinbefore have led IRSN to propose to the working group measurements in order to reduce the risk of self-loosening of packages impact limiter fastening bolts under vibrations during shipment.

In particular, it appears that an **increase of the pre-load** of the impact limiter fastening bolts is the most efficient way to reduce the risk of bolts self-loosening during the transport of the packages involved in the events described hereinbefore. Based on the equations proposed by Fernando [REF 5], the consequences of an increase of the initial bolt pre-load on the minimum frequency and amplitude of the vibrations required to start loosening are presented in Figure 2, where the pre-load (F) is expressed as a fraction of the bolts yield strength (Sy).

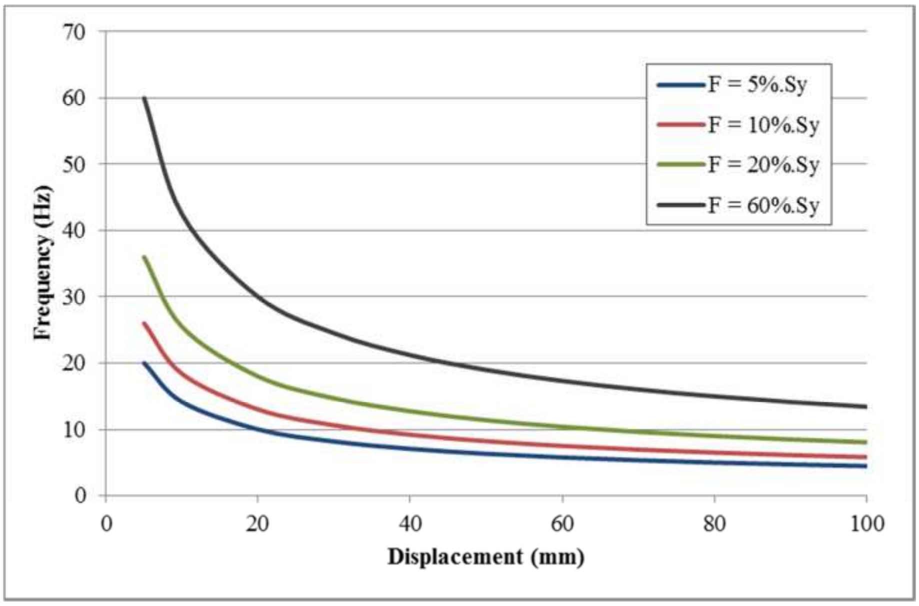

Figure 2: Minimum frequency to initiate self-loosening according to the vibration amplitude and the initial bolt pre-load (F)

As shown in equation (1), the most direct way to increase the bolt pre-load (F) is an **increase of the tightening torque** (T).

$$F = \frac{T}{0{,}159.p + 0{,}583.\mu_t.d + \mu_h.r_h} \qquad (1)$$

Where: F is the bolt pre-load,

T the tightening torque,

p the thread pitch,

μ_t the friction coefficient in the threads,

μ_h the friction coefficient under the bolt head,

r_h the average bearing radius under the head.

Nevertheless, due to a risk of yielding of the bolted components, especially located under the bolts head, the tightening torque in the packages impact limiter fastening bolts cannot be increased up to a value leading to a pre-load equal to 65% of the bolt yield strength. In this regard, an increase of 50% of the initial tightening torque has been implemented by the AREVA TN company in the operating instructions of the packages involved in the recent events. The positive results of this action have been confirmed on the basis of tightening and loosening tests performed on an impact limiter equipping one of the packages involved in the previous events.

Besides, the cleanliness of the threads is another way to reduce the risk of bolts self-loosening for a given package design. In this regard, measures such as the storage of the bolts in a dry and clean environment, the closure of the threaded holes of the packaging after the bolts removing operation and the threads cleaning before tightening has been recommended to packages users.

Definition of a dedicated experimental program

The recommendations made hereinabove are based on generic conclusions drawn from the theories and experimental tests presented in references [REF 1] to [REF 5]. Nevertheless, these studies put in the light the necessity to take into account the characteristics of the bolted components and those of the vibrations occurring in routine conditions of transport in order to precisely analyse the risk of bolts self-loosening and to propose adequate measures to reduce this risk.

In this regard, IRSN is currently defining a dedicated experimental program using a shock absorber designed and manufactured by the AREVA TN company to determine precisely under which conditions the self-loosening of packages impact limiter fastening bolts can be initiated.

The principle of this program will be to place a real impact limiter equipping one of the packagings involved in the last self-loosening events on a shaking table and to analyse the bolts behaviour subjected to vibrations. For this purpose, the impact limiter will be provided by the AREVA TN company and the vibrations will be similar to those measured by the AREVA TN company on the package conveyance during road and rail transports.

During the test, the impact limiter will be fastened on a structure (supporting frame) sufficiently rigid to simulate the mechanical behaviour of the heavy package under vibrations (see Figure 3). A specific attention will be paid on the eigenfrequencies of the supporting frame which should be higher than the excitement frequencies simulated during the tests.

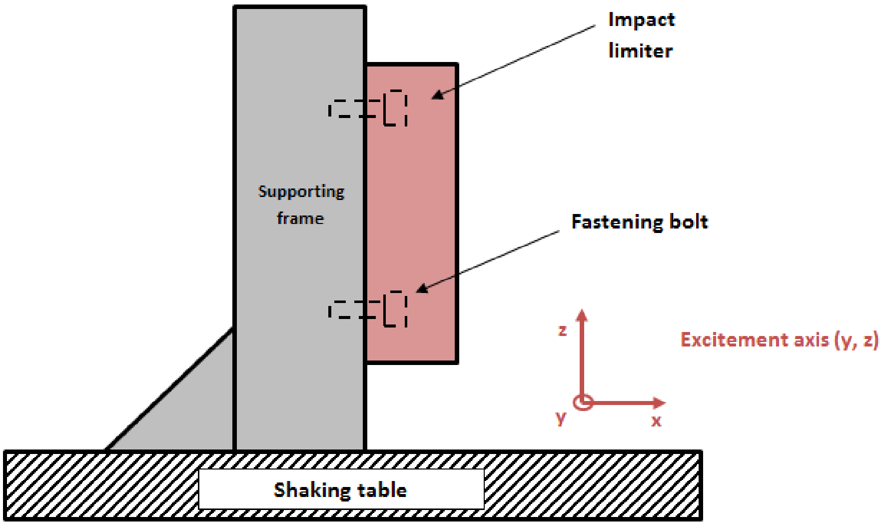

Figure 3: Schematic drawing of the experimental device

As dynamic transverse loads are the most damaging in terms of self-loosening, the use of a bi-axial shaking table (with a vertical and a lateral excitement axis) would be sufficient. Moreover, the performances of the table selected for this experiment fit the characteristics of the vibrations measured during transport in terms of maximum displacement and excitement frequencies.

The objective of the experimental program will be to analyse the impact on self-loosening of several parameters involved in the tightening conditions, such as:

- the tightening torque, in order to assess whether the updated value proposed by the package designer is sufficient to reduce the risk of self-loosening in all means of transport (rail and road);
- the tightening order, to evaluate the impact of possible mistakes during tightening operations (tightening order different from the “cross” or “star” order currently recommended for all package designs);
- the threads surface condition, in order to assess whether the presence of impurities can increase the risk of self-loosening;
- the use and the type of lubricant and its location (on the threads, under the bolt head), in order to confirm the impact of the friction coefficients on the self-loosening phenomenon.

At the end of this experimental program, it is expected to have a better understanding of the bolts self-loosening phenomenon in the context of the road and rail transport of heavy packages and to conclude on the relevancy and the sufficiency of the corrective actions put in place by applicants and operators in order to limit the occurrence of further similar events.

Conclusions

Several analysis and theories have been conducted and developed in the past decades in order to explain and to quantify the bolts self-loosening phenomenon. A review of these results puts in the light that the bolts self-loosening is favoured by vibrations characterised by high frequencies and amplitudes. In addition, the impact of several parameters, including bolt dimensions, bolt pre-load and friction coefficient, have been identified by the authors.

Considering the vibrations measurements performed during road and rail transports on heavy package designs, IRSN has recommended to the working group, when operationally possible, an increase of the tightening torque of the impact limiter fastening bolts for some package designs. Nevertheless, this analysis puts in the light the necessity to conduct experiments using a real shock absorber to evaluate precisely under which conditions the self-loosening of packages impact limiter fastening bolts can be initiated.

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